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# **COMPACT, HIGH POWER, REPETITIVE PULSED POWER INSTRUMENTATION**

## **FINAL PERFORMANCE REPORT January 2004**

**AIR FORCE OFFICE OF SCIENTIFIC RESEARCH**

**GRANT #: F49620-02-1-0228**

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## **"Compact, High Power, Repetitive Pulsed Power Instrumentation"**

**AFOSR Grant No. F49620-02-1-0228**

**Final Report                  June 15, 2002 – December 14, 2003**

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### **Abstract**

The vacuum system, pulse generator and oscilloscopes are used for pseudospark-BLT switch research. The pumping system is for achieving necessary high vacuum conditions. Observations of cell membrane perturbation in real time with sub-nanosecond time resolution is made possible by the PicoStar HR-12 CCD camera system and its custom table purchased under this AFOSR Grant. This High-Speed CCD camera system is a component of AFOSR-supported Transient Plasma Ignition research as well. The scopes and pulse generator provide diagnosis, analysis, and control of experiments requiring accurate, fast diagnostics. Implementation of these systems has enabled results in pulsed power switching, and applications of pulsed power to biology, and ignition and combustion. Switching research includes investigation of small BLT switches for compact pulse generation, which will be reported this year at an AFOSR MURI review, and technical meetings including the Intl. Conf. on Plasma Science. Biology includes real-time observation of Ca bursts in human lymphocytes, reported in Biophysical and Biochemical Research Communications, and at other reviews and conferences. Ignition includes development of transient plasma ignition, which reduces delays to ignition in applications such as pulse detonation engines.

### **Acquired equipment**

<b><u>Cost</u></b>	<b><u>Source</u></b>	
PicoStar HR-12 CCD camera system	La Vision GmbH	\$97,095
Custom table for CCD camera system	Technical Manufacturing Corp.	\$ 5,704
TiPS 300 dry turbo pumping system	Leybold Vacuum Products	\$ 9,487
Digital delay/pulse generator	Stanford Research Systems	\$ 5,644
TDS694C digital storage oscilloscope	Test Equity	\$30,479
Tektronix TDS5104 oscilloscope	Test Equity	\$13,228

### **Research Summary**

Compact, portable, very high peak pulsed power that is robust, repetitive and lightweight has remained an elusive goal notwithstanding tremendous advances in solid state technology and modern innovations in fabrication. Remarkable advances in optoelectronic devices, electronic device design, growth, and performance offer the prospect of new approaches to architectures and components for repetitive pulsed power for high power applications; however, physics limitations related to applications for pulsed power remain unresolved, and in some cases add limitations not obvious for low voltage and power applications. High performance switches remain key limitations for high voltage and high current, fast, repetitively pulsed circuits. Recent research in our laboratory concentrated on several novel and basically different approaches to the implementation of advanced switching devices and their implementation in efficient voltage multiplication architectures. An approach that shows promise utilizes super-emissive gas-phase switches including the pseudospark and back-lighted thyatron to enable very compact pulsed

power generators with low load impedance. Our research examined the physics issues implicit in approaches with both the gas-phase switches and semiconductor switches, and how these can be approached to provide a basis for design of compact, repetitive pulse generation at high power, and show the implementation of devices into pulsed power architectures for a range of applications.

High intensity ( $\sim 2.5$  MV/m) short duration (ns & sub-ns) pulses can affect the intracellular structures without adversely affecting the outer cell membrane. An interesting effect of such pulses is apoptosis or programmed cell death. Observations of cell membrane perturbation in real time with sub-nanosecond time resolution is made possible by the PicoStar HR-12 CCD camera system and its custom table purchased under this AFOSR Grant. This High-Speed CCD camera system is an essential component of our Transient Plasma Ignition research as well.

Generation of high voltage short duration pulses require fast switches and one or more pulse compression sections. Blumlein pulsed forming networks (PFN) are the most common circuit topology used for short pulse generation. The pulse shape and the rise/fall time of the pulse delivered to the load, depends on the response time of the switch and the characteristics of the Blumlein. Traditionally, the transmission line structures used in the Blumlein are modeled as ideal elements. At shorter pulse widths, the Blumlein models must account for the input and output edge effects, the distributed nature of the load, and the effects at Blumlein-load interface. We have generated a simple spice model to simulate the edge effects of a short Blumlein. The model shows that edge effects limit the achievable minimum pulse width and rise/fall times. Practical implementations of fast high voltage pulse generators based on such Blumlein transmission lines necessitate the precise measurement of pulse voltage and current. The essential component of such high speed measurements is the TDS694C digital storage oscilloscope purchased under this AFOSR contract.

A compact inductive adder is being designed for use as a building block in larger pulse generator systems or as a modular component for pulsed power applications. The solid-state inductive adder uses MOSFETs instead of pulse forming networks to directly drive mumetal magnetic cores. It produces pulses 0-6kV with 10-40ns widths. The pulse generator is matched to 50-ohm load or transmission line.

Spark gap switched transmission line pulse generators can achieve faster switching by overvoluting the spark gap with high amplitude nanosecond pulses. A fast spark gap trigger permits a slow charging source, thus allowing more simple and compact charging networks. A solid state transmission line transformer (TLT) has been designed and constructed for triggering spark gaps in the overvolted mode. The spark gap trigger source is itself simple and compact so that it may be integrated with pulse generator systems. A four stage discrete element TLT is pulsed by a totem pole MOSFET driver. Resonant voltage rise effects are taken advantage of by the use of discrete element transmission lines.

We have carried out simulation and analysis of a 4H-SiC JFET. For pulsed power applications, this structure is intended to incorporate conductivity modulation characteristic of an IGBT so that it will achieve a higher blocking voltage and higher current density. ATLAS is used to investigate the current flowlines, voltage blocking capability,  $I_d$ - $V_d$  characteristics and switching performance in the 4H-SiC JFET. The goal of the work is to compare SiC JFET with its silicon and GaAs counterparts, and provide guidelines for pulsed power applications. We intend to fabricate such devices and incorporate them into our pulse generators, evaluating the practical limits on such semiconductor switches.

An essential measurement tool for all such high-speed pulse generator work is the Fast Tektronix TDS5104 oscilloscope purchased under this AFOSR Grant.

We have designed and constructed a pulse forming circuit and a command resonant charger for Transient Plasma Ignition. The pulse generator incorporating this pulse forming circuit is based on a gas phase switch, the Pseudospark, developed in this laboratory and now commercially produced in Germany. This application - corona assisted flame ignition and combustion - This application requires operation of the Pseudospark switch at 30kV charging voltage and 1 kHz repetition rate. The charging time of the 6nF / 30kV quasi Blumlein pulse forming circuit capacitance is 50 $\mu$ s. Operation is burst mode, with maximum 100 pulses per burst. A single stage lumped element Blumlein and a 1:3 Metglas-polyethylene-foil core transformer were employed to create high-voltage (80kV) short-duration (50ns) pulses. Combustion precursors and radicals produced by the fast transient plasma are substantially different from conventional spark ignition, with many applications. Studies of the chemical composition and its evolution in the early stages of the transient plasma induced combustion are carried out by real time spectroscopy based on the PicoStar HR-12 CCD camera system purchased under this AFOSR Grant.

We have designed a Marx style pulse generator using advanced Pseudospark switches. The bank consists of three 150nF / 40kV capacitors connected with three floating FS2000 type Pseudospark switches. These switches can hold off 35 kV and pass up to 10 kA at repetition rates approaching 1 kHz. The expected lifetime of >200kC and the relatively low housekeeping power of <50 W make the Pseudospark switch an excellent candidate in compact Marx generator applications. The design and construction of the floating power supplies and trigger units, and the synchronized triggers essential to the successful operation of such a Marx generator rely on the Stanford Research Systems Digital delay/pulse generator purchased under this AFOSR Grant.

An advanced, multi-gap Pseudospark device is under development in our laboratory. Forced grading of the intermediate electrodes in the switch will be achieved by taps on the charging transformer. Gap synchronization is aided by UV illumination of all gaps from the primary gap trigger. The switch is intended to be the critical part of a 500 kV, 10 kA, 200 ns Transmission Line Transformer based pulse generator. The TiPS 300 dry turbo pumping system purchased from Leybold is an essential element in this program.

**The following publications present research carried out with the help of instrumentation purchased under this Grant:**

F. Wang, A. Kuthi, and M. Gundersen, “Pseudospark Based Pulse Forming Circuit For Transient Plasma Ignition Experiments,” 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper T3-8.

P. Wijetunga, X. Gu, P. T. Vernier, A. Kuthi, M. Behrend and M. A. Gundersen, “Electrical Modeling Of Pulsed Power Systems For Biomedical Applications,” 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) Invited paper, T7-1,2.

X. Gu, P. Wijetunga, A. Kuthi, M. Behrend and M. A. Gundersen, “Nanosecond Rise Time Minipulser For Cell Electroperturbation,” 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper MP-86.

M. Behrend, A. Kuthi, and M. Gundersen, “Solid State Tlt For Spark Gap Triggering,” 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper MP-90.

M. Behrend, A. Kuthi, M. Thu, Q. Shui, P. Wijetunga, and M. Gundersen, “Direct Mosfet Drive 20 Nanosecond Compact Inductive Adder,” 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper MP-91.

A. Kuthi, R. Alde, M. Gundersen and A. Neuber, “Marx Generator Using Pseudospark Switches,” presented at the 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper W8-1.

A. Kuthi, B. Eccles, Qi. Yao, C. Jiang, K. Frank and M. Gundersen, “Advanced Multi-Gap Pseudospark Switch,” presented at the 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper MP-87.

A. Kuthi, C. Young, F. Wang, P. Wijetunga, and M. Gundersen, “Rapid Charger For High Repetition Rate Pulse Generator,” presented at the 14<sup>th</sup> IEEE Int. Pulsed Power Conf., (2003) paper MP-88.

M. Behrend, A. Kuthi, Xi. Gu, P. T. Vernier, L. Marcu, C. M. Craft and M. A. Gundersen, “Pulse Generators For Pulsed Electric Field Exposure Of Biological Cells And Tissues” accepted for publication in IEEE Trans. on Dielectrics and Electrical Insulators.

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P. T. Vernier, M. Thu, L. Marcu, C. M. Craft, and M. A. Gundersen, “Nanosecond electroperturbation — mammalian cell sensitivity and bacterial spore resistance”, in press, *IEEE Trans. Plasma Sci.*, 2004.

Y. Sun, P. T. Vernier, M. Behrend, L. Marcu, S. Salemi and M. A. Gundersen, “Non-Invasive Approaches to Nano-Biology Through Advanced Pulsed Power”, Workshop on High-Field Effects and Fast Pulse Responses in Bio-Systems, IEEE Conference on Electrical Insulation and Dielectric Phenomena, October 19–22, 2003, Albuquerque, NM.

P. T. Vernier, Y. Sun, L. Marcu, S. Salemi, C. M. Craft, and M. A. Gundersen, “Field-Dependent, Non-Invasive Intracellular Electroperturbation of Human Lymphocytes”, Workshop on High-Field Effects and Fast Pulse Responses in Bio-Systems, IEEE Conference on Electrical Insulation and Dielectric Phenomena, October 19–22, 2003, Albuquerque, NM.

P. T. Vernier, A. Li, L. Marcu, X. Zhu, C. M. Craft, and M. A. Gundersen, “Nanosecond, Megawatt, Millijoule Pulses Translocate Membrane Phospholipids and activate Caspases in Malignant Cells” ElectroMed 2003, June 11–13, 2003, San Antonio, TX, paper in *Proc. Third International Symposium on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases* (ElectroMed 2003), p. 65.

P. T. Vernier, L. Marcu, Y. Sun, S. Salemi, C. M. Craft, and M. A. Gundersen, “Real-time imaging of mammalian cells in nanosecond, megawatt, millijoule pulsed electric fields”, *BiOS* 2004 (SPIE), San Jose, Jan. 2004.

F. Wang, C. Jiang, A. Kuthi and M. A. Gundersen C. Brophy and J. O. Sinibaldi, L. C. Lee, “Transient Plasma Ignition of Hydrocarbon-Air Mixtures in Pulse Detonation Engines”, 42nd Aerospace Sciences Meeting, 6th Weakly Ionized Gases Workshop, Reno, Nevada 5 - 8 Jan 2004. Paper published in AIAA Proceedings.

M. Gundersen, “Plasma Enhanced Ignition: Challenges and Overview”, Presentation, Workshop on Understanding Plasma Ignition, Stanford University, Jan. 9, 2004.

J. B. Liu, N. Theiss, P. D. Ronney, M. Gundersen, “Minimum ignition energies and burning rates of flames ignited by transient plasma discharges”, 2003 meeting of Western States Section/Combustion Institute, Oct. 10-11, 2003.